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EFFECTS OF ADVANCES IN PROPULSION TECHNOLOGY ON MISSILE EFFECTIVENESS

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ABSTRACT

This paper presents the effects of propulsion technology evolution on the performance capability of advanced missile systems. The evolution of the missile propulsion system from rocket to ramjet with increased emphasis on advanced airbreathing missile cycles, has significantly extended missile operational capabilities. The development of these new areas of ramjet technology, specifically in solid fuel propellants, offers the advantages of large increases in heating value, density, burning efficiency and improved system packaging. Application of these technology advancements to potential mission scenarios produces impressive increases in overall mission performance. These large performance gains provide a basis for improvements in mission effectiveness in terms of kill probability and survivability. Kill probability is increased by application of shorter intercept times, improved multi-shot capability and reductions in individual system size to improve weapon carrier payload capability. Survivability is enhanced by increased standoff distances and higher penetration velocities. Demonstration of these improved capabilities, over a variety of tactical mission are provided by a direct comparison of missile performance for a variety of missile propulsion systems. The systems studied range from the conventional solid rocket system to the advanced highly energetic boron solid fuel ramjet concept.

Letter on file

INTRODUCTION

The use of missile systems has become an important part of the total tactical warfare environment due to the increased effectiveness of these systems in destroying high value enemy targets on land, sea, and air. Development of these tactical missile systems has been historically paced by the development of electronic technology in terms of target acquisition and guidance. Currently, the emphasis on electronic technology must be supplemented by advances in propulsion technology to counter the continued sophisticated upgrading of the enemy defenses. As sophistication of the enemy defenses increases, the effectiveness of the missile systems become more complex due to the added requirement of missile survivability as well as kill probability. In general terms, the missile effectiveness (E) can be defined in terms of the probability of survival against the defense (Ps) and the probability of killing the target (Pk) in the form:

$$E = Ps \times Pk$$

The missile system survivability is dependent upon the standoff distance at launch, the pentration velocity, the missile maneuverability, the missile visibility (radar cross section and infrared), and electronic countermeasures. Kill probability is dependent upon guidance, target acquisition, terminal maneuverability, time to target, number of missiles available, and versatility of each missile. To obtain these missile effectiveness requirements, advances in propulsion system technologys are becoming increasingly important along with electronics development. This paper intends to show the role of advanced propulsion technology evolution on the performance capability of advanced missile systems. Specific areas where propulsion technology offers the most potential in improving missile system effectiveness are standoff distance, terminal velocity, weapon system size, versatility, and maneuverability. Propulsion system technology advancement has occurred in two major directions of effort, those associated with the development of new propulsion system cycles, such as the use of air augmentation for ramjets and ducted rockets, and the development of new more energetic fuels having higher heating values and improved burning efficiency. A brief summary of the historical development of these two areas of propulsion development are presented as a review for the reader, followed by a discussion of their impact on the missile system effectiveness.

PROPULSION TECHNOLOGY DEVELOPMENT

Propulsion system development for the tactical environment has mainly concentrated on solid propellants instead of liquid fuels, due to the inherent simplicity, reliability, low cost, and long storage life of a solid fuel system. Systematic advances in missile cycle technology for these solid fuel systems have increased missile potential performance capabilities significantly over the past decade. As a result of these advances, the array of potential propulsion system cycles available for missile deployment ranges from the solid single phase rocket to the advanced solid fuel ramjet, as shown in Figure 1. These systems represent a spread from current state-of-the-art to advanced systems still in the conceptual R & D phase. The following paragraphs present a brief description of each of these propulsion cycles.

The current tactical missile arsenal is mainly composed of solid propellant rocket powered systems, Figure 1A, providing a large initial impulse to boost the missile towards the target. The main disadvantages of these systems are that while large thrust levels may be obtained, the booster duration is rather short due to the required high burn rate of the propellants. This means that the missile is

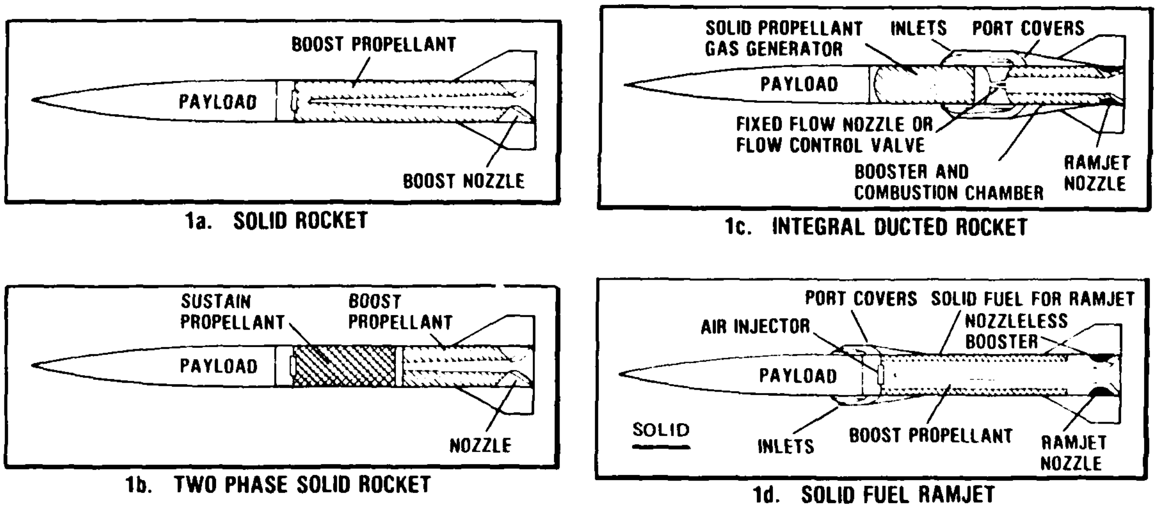

Figure 1. Propulsion System Concepts

under powered thrust only during the initial portion of the flight, and once the booster has burned out, the missile continuously decelerates towards the target. This places large restrictions on the missile range capabilities. To help alleviate this problem, recent advanced missile systems, such as stinger, have gone to a two phase solid propellant motor, as shown in Figure 1B. In the two phase system, an initial high burn rate propellant provides the high thrust level required to boost the missile up to the desired flight velocity followed by a slower burn rate sustainer propellant to provide the low thrust level required for sustained cruise. The use of the boost/sustain solid motor concept provides a better than 2 to 1 increase in the missile powered range capability.

In the solid rocket motor, the propellant formulation contains both the fuel plus all the oxidizer required for combustion throughout the flight. In a typical system, the oxidizer accounts for over 85% of the total propellant weight. The carrying of this oxidizer weight directly relates to a reduction in the missile payload-range capabilities. To overcome this weight penalty, the ducted rocket concept is being developed, in which freestream air is used to supplement a portion of the required oxidizer during the sustain portion of flight. Typically, the oxidizer can be reduced to 35% of the total weight. In the ducted rocket concept, the initial boost propellant is loaded integrally into the missile aft, end as illustrated in Figure 1C. At the end of the boost phase, the inlet port covers are opened and the ducted rocket propellant ignited. The freestream air flows through the inlet and mixes with the fuel rich ducted rocket exhaust in the combustion chamber formed by the expended booster propellant. The air augmentation allows the system to achieve efficient combustion at low fuel flow rates, significantly extending the sustained portion of the flight. The ducted rocket propulsion system is currently under developemnt in the U.S. and should be flight tested next year.

Further reductions in sustain oxidizer requirements are being evaluated as part of the Solid Fuel Ramjet Technology Program currently being pursued in the U.S. on a research basis. The Solid Fuel Ramjet Concept employs fuel with no oxidizer over which the inlet air flows to generate a combustable mixture, as shown in Figure 1D. The booster propellant is placed over the sustainer grain and is used to preheat and ignite the sustainer grain. Besides the advantage of eliminating the oxidizer, the solid fuel ramjet concept also provides the capability of self throttling at high altitudes, thereby allowing the system to operate at near optimum fuel flow over the entire flight envelope. The solid fuel ramjet represents an advanced simple concept which should approach the maximum missile performance made possible with a solid fuel system. The solid fuel ramjet development is currently in the research phase with flight demonstrations planned within the next 5 years.

In the area of advanced propellant development, the effort is directed towards achieving the advantages of large increases in heating value, density, burning efficiency, and improved system packaging available from the more exotic fuels. The combination of increased fuel heating value and density creates the potential for fuels with very high volumetric heat release, providing the capability to package significantly more BTU's per cubic inch of missile volume. A comparison of the relative energy content of a number of advanced fuels is shown in Figure 2, using JP4 as a base line. On both a volumetric and gravametric basis, boron is seen to be the most attractive fuel for obtaining high energy release, showing over a 3 to 1 advantage in potential volumetric heating value compared to JP4. The integration of high energy fuels such as boron into a missile system provides significant mission advantages such as increased range,

FUEL	GRAVIMETRIC HEATING VALUE	VOLUMETRIC HEATING VALUE
JP-4	1.0	1.0
SHELLDYNE	0.95	1.33
MAGNESIUM	0.54	1.20
ALUMINUM	0.71	2.40
BORON	1.25	3.83

Figure 2. Comparison of Fuel Heating Values.

higher intercept velocities, reduced vehicle weight, and lower time to target. When these fuels are combined with the advanced propulsion cycles discussed earlier, the potential missile performance improvements are very large. Research programs for the development of boron fuels are currently being funded by the USAF. To date, successful firings of a boron solid fuel ramjet have been achieved in a direct connect air augmented facility, demonstrating high delivered volumetric heating values with high combustor efficiency. Additional USAF funded programs are underway for advanced boron ducted rocket studies and development of boron slurry fuels.

STANDOFF RANGE

The enemy defensive shield is continuously expanding as they implement advances in technology. Typical current SAM air defenses, as projected for the Soviet army, are shown in Figure 3. These outer boundaries will be expanded even further as new weapons arise and are incorporated into the defense line,adding over a 50% increase in range capability. Similar expansion exists in the Soviet air-to-air capability as new technology continuously increases the AAM ranges. In view of this ever increasing defensive shield, our tactical weapon launching platforms become increasingly vulnerable to destruction prior to initiating their attack. Hence a weapons system survivability becomes an important factor in determining the mission success. A key element in increasing survivability against this defensive threat is to extend the standoff distance of the launch platforms. By increasing the standoff distance, the burden of the extended trajectory range falls on the missile system. The missile propulsion system becomes the major contributing factor in obtaining the required increased missile range. Through the use of advanced propulsion cycles and more energetic propellants, current missile system ranges may be extended significantly beyond present enemy defense capabilities.

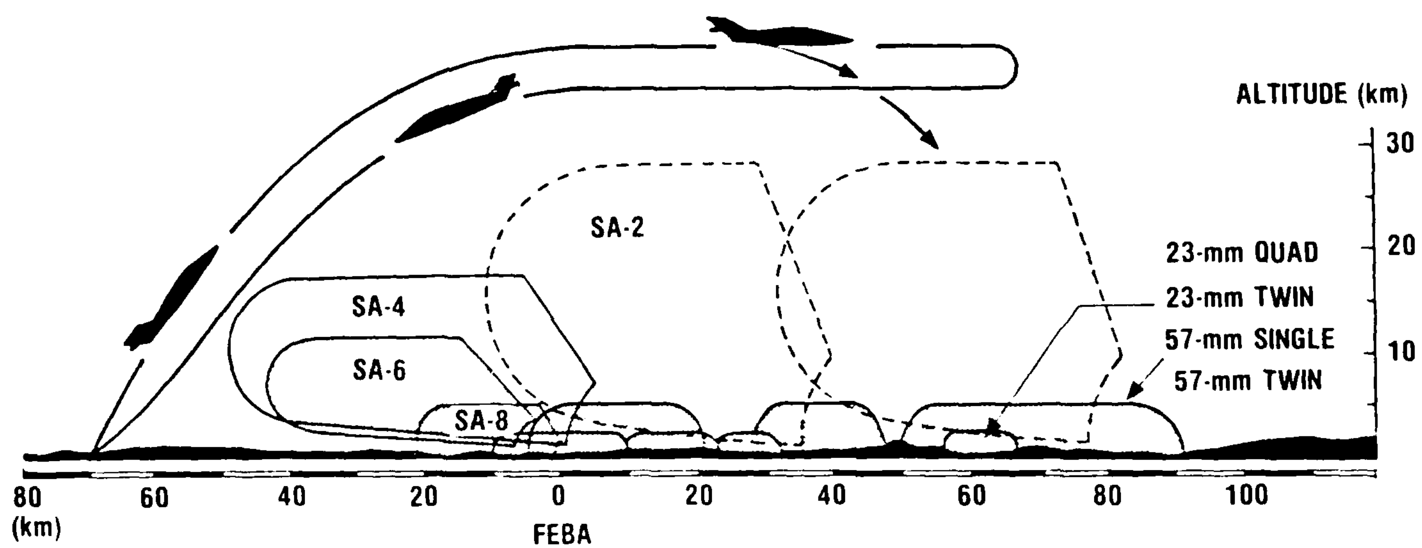

Figure 3. Surface-to-Air Defense of Soviet Army.

A comparison of the potential propulsion system advances discussed in Figure 1 on the missile standoff range capabilities are shown in Figure 4 for a typical air launched missile system. The use of a two phase boost/sustain rocket motor nearly doubles the flyout range capabilities of the pure boost system. The addition of air augmentation for the sustain phase as in the ducted rocket concept more than doubles the flyout range capabilities again over the two phase rocket. The hydrocarbon solid fuel ramjet concept which carries no internal oxidizers for sustained flow, relying completely on free-stream air flow for combustion, shows even another nearly two for one increase in range. The last bar shows the advantages of combining the highly energetic boron fuel with the solid fuel ramjet concept. As can be seen, the use of boron as a solid ramjet fuel offers tremendous advantages in range capabilities. The trends shown for the air launched missiles will apply equally well to ground launched systems. In fact, the high energy boron fuel will appear even better due to the increased acceleration available at low altitudes.

MISSILE VELOCITY

Speed and agility greatly improve the effectiveness of a missile system by increasing both kill probability and enhancing survivability. Increased missile velocities during the terminal target engagement enhance the kill probability by adding excessive maneuver energy relative to the target. If the missile has a high energy level relative to the target at the time of intercept, the target will not be able to out maneuver the missile and escape the lethality pattern of the warhead. In addition, high intercept velocities reduce enemy reaction time, thereby allowing less time for evasive or defensive action. Survivability is enhanced at higher missile velocities by reducing the time for radar detection and lockon by limiting defensive reaction time. An example of the advantages of missile penetration

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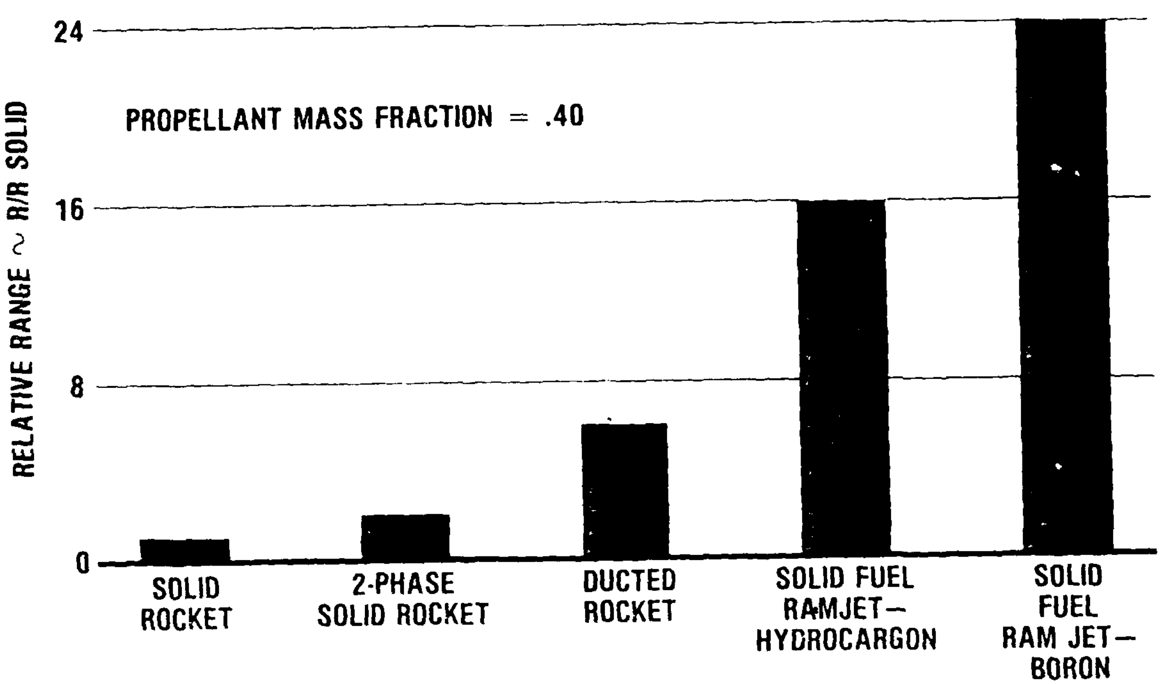

Figure 4. Propulsion System Fly Out Range Comparison.

velocity on survivability probability against a SAM missile intercept is shown in Figure 5. As can be seen high penetration velocities quickly reduce the intercept capability of the defense, increasing the probability of a successful mission.

The effects of the propulsion system selection on the missile velocity capabilities are shown in Figure 6. The solid rocket system normally will achieve the highest velocities during the boost phase, but at the end of the relatively short boost period the missile will quickly decelerate. This means that at the time of terminal engagement the solid rocket may not have adequate maneuvering energy to acquire and kill a target taking evasive action if the launch range is very far. The air augmented systems on the other hand, allow the missile to achieve sustained flight at supersonic speeds over long ranges, thus providing the terminal energy needed for successful kills at extended standoff ranges.

Higher missile velocities also enhance kill probability by increasing the number of firings that may be made in shoot-look-shoot type scenarios. A typical example of this type effect is shown in Figure 7 for a standoff jammer intercept. A 15 second delay was assumed between each firing to account for reaction and response time. These results show that by doubling the missile velocity the number of possible intercepts is doubled, with a proportional increase in kill probability. Again it must be stressed that for the large standoff ranges of a jammer system, only the air augmented propulsion systems possess the velocity and range capabilities to make a kill. For the particular standoff jammer scenario shown, very high average velocities are required to minimize the time to intercept required for multiple firings, illustrating application where very highly energetic fuel or even supersonic combustion scramjets would be required. These are areas where further advanced propulsion development may show high payoffs.

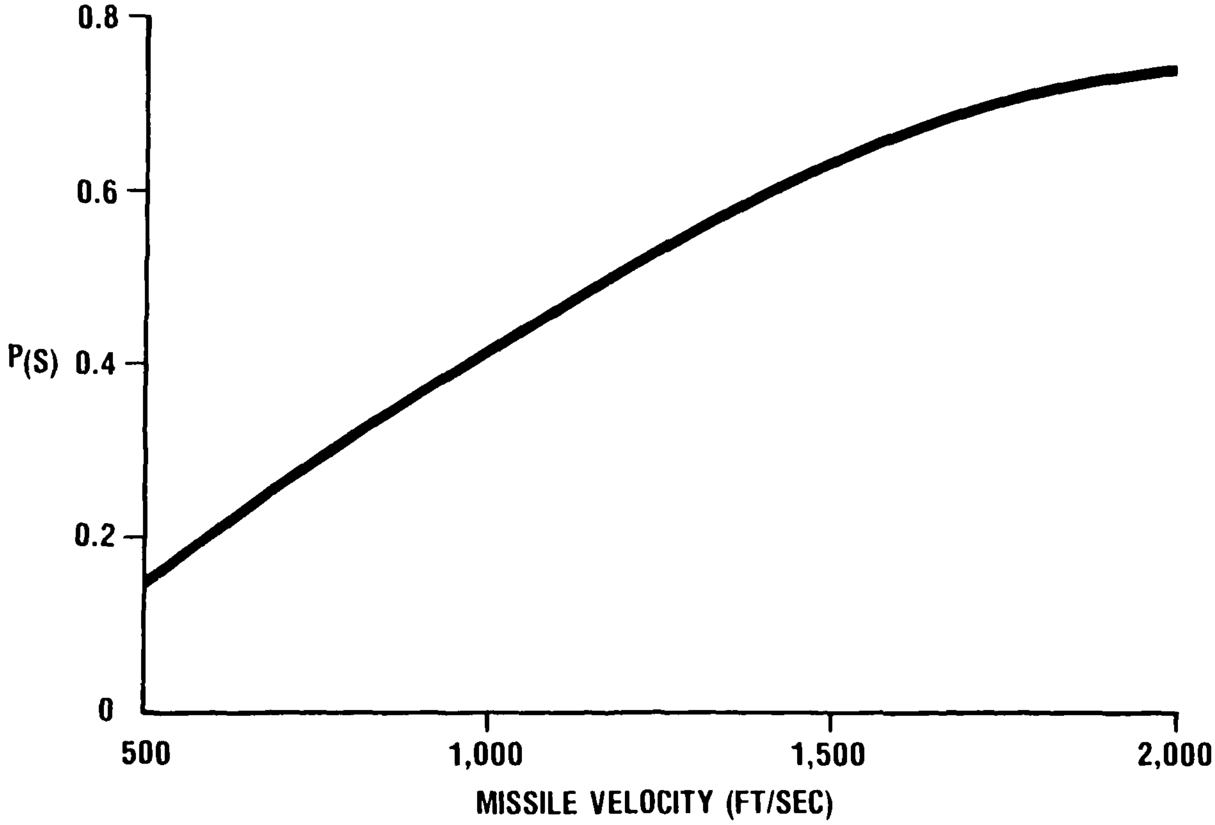

Figure 5. Missile Survivability Characteristics against Missiles.

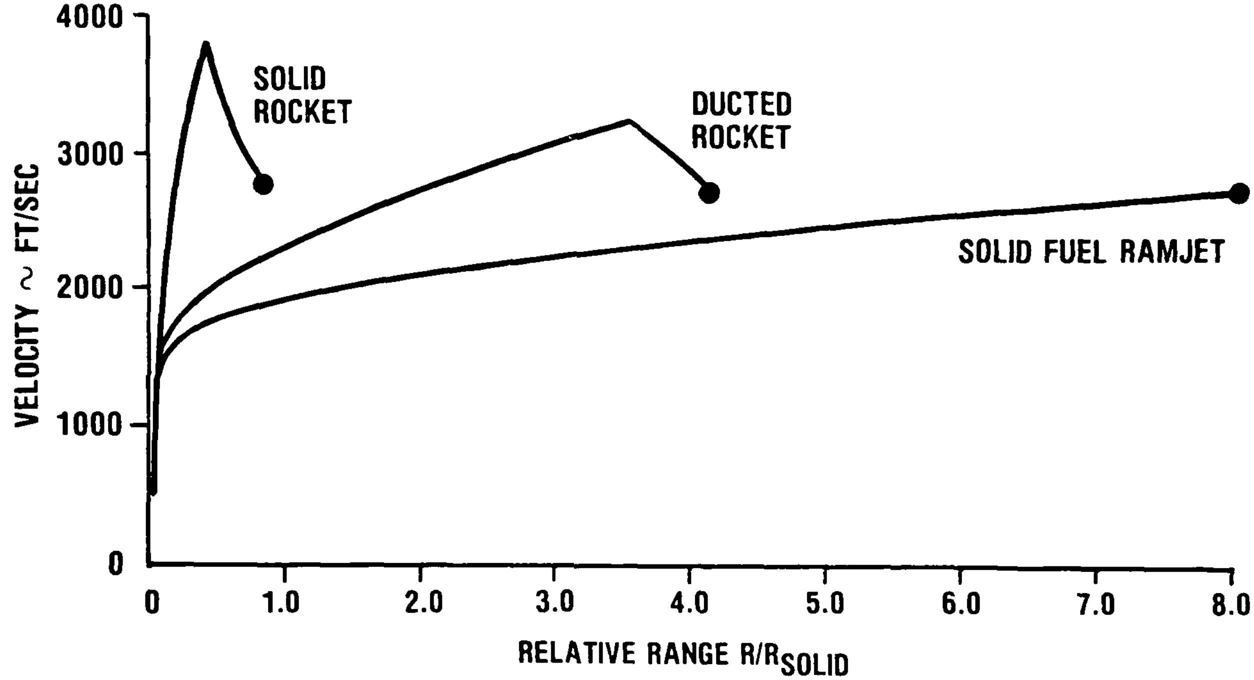

Figure 6. Propulsion System Velocity/Range Comparisons.

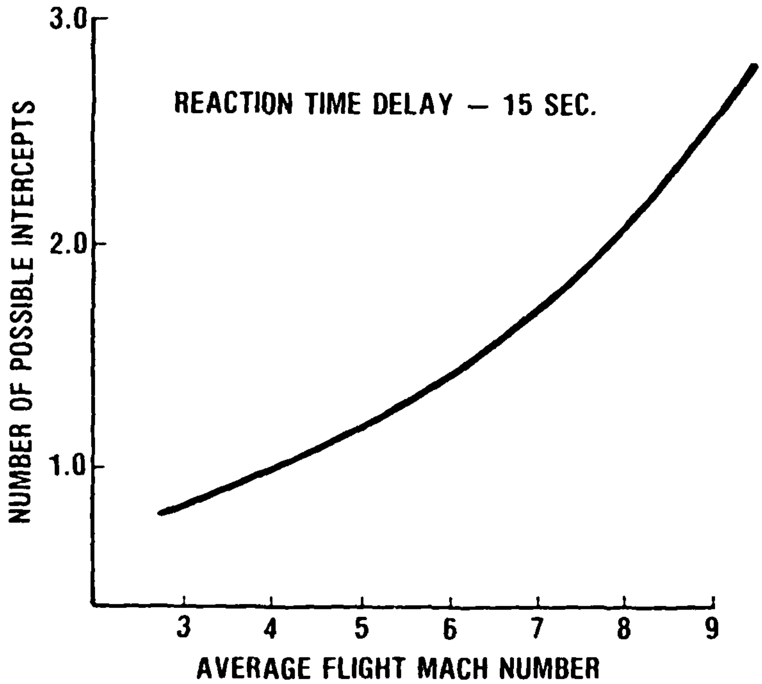

Figure 7. Effect of Average Flight Mach Number on Number of Intercepts Against A Standoff Jammer.

MISSILE SIZE

The success of an engagement is directly related to the number of weapons available for firing. Therefore, the number of missiles which can be carried by a given launch platform is an important factor in determining the missile system's effectiveness. In an air launched attack, the system's effectiveness can be defined as the number of targets destroyed per attacking launch aircraft (N_m) as well as the survival (Ps) and kill (Pk) probabilities of the individual missiles. Therefore, the importance of maximizing the number of missiles which can be carried having fixed (Ps) and (Pk) against the desired target is apparent. This emphasizes the importance of reducing missile size for fixed performance levels as a worthy goal for technological development.

Missile size may be constrained by both volume and weight limitations of the carrier platform. Normally in aircraft stores loading, volume, or space is the limiting factor where maximum payload becomes of secondary importance. Therefore, to optimize a weapon system's effectiveness one must maximize the number of missiles for the total stores carrying volume capacities. Within this total volume restriction, the propulsion system of each missile must be sized to perform the desired mission role. Propulsion system sizing is determined by the system density and the energy level of the fuel. In a volume limited missile, the fuel heat release per unit volume or volumetric heating value is the important design factor. The fuel volumetric heating value determines the amount of missile volume required to package the desired propulsion impulse. Hence, it is desirable to use fuels with high volumetric heating value to minimize missile size. High volumetric heating values are also beneficial for weight limited missiles. The smaller missile volume required for packaging the propellant results in a reduction in the total missile structural weight. This reduced structural weight may be offset by increasing the total propellant weight with its resultant increase in total impulse. A comparision of the relative vehicle size versus the volumetric heating values for a number of different propulsion systems are shown in Figure 8. The high density, high heating value of the boron solid fuel ramjet provides the best solution for maximizing the number of missiles which can be carried in a volume limited situation. The use of boron in the other airbreathing cycles also provide a means of significantly reducing missile volume.

VERSATILITY

To maximize the use of a tactical weapon system, each missile system should be as versatile as possible, allowing it to be deployed against a variety of targets. This versatility will greatly reduce the total mix of tactical weapons required and enhance fire power against any specific target, thus, eliminating the need for special missile systems to attack or defend against specific targets.

The secret to a versatile missile system is through the use of energy management within the propulsion system. Energy management may be obtained through the use of the variable mode solid fuel ramjet concept.

The Variable Mode Solid Fuel Ramjet (VMSFRJ) is a concept which combines radial pulse technology and the solid fuel ramjet propulsion system to maximize vehicle operational flexibility. This approach utilizes discrete solid propellant grains covered by a thermal protection system, as shown in Figure 9, which can be selectively fired to achieve a required mix of boost mode and airbreathing mode for operation against a wide rariety of threats. Recent testing of this concept at Atlantic Research Corporation, under contract to the

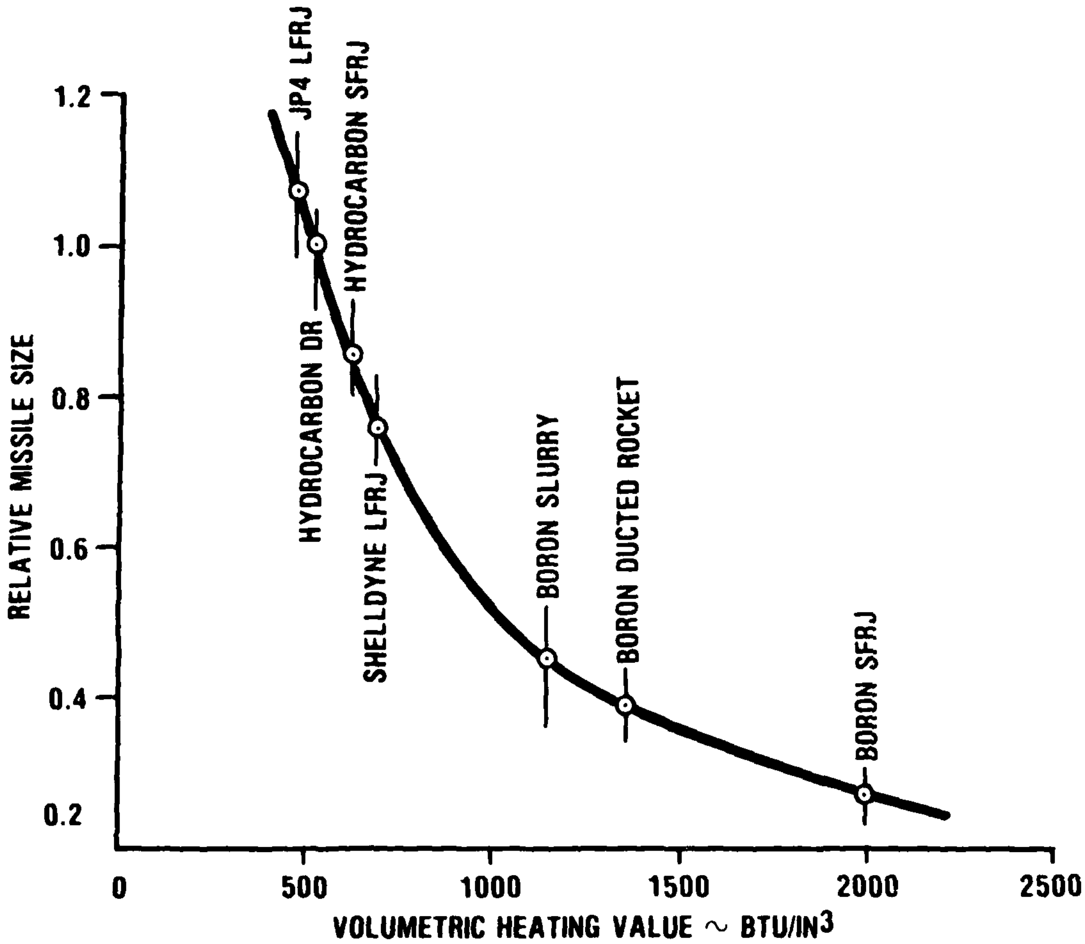

Figure 8. Effect of Heating Value on Missile Size.

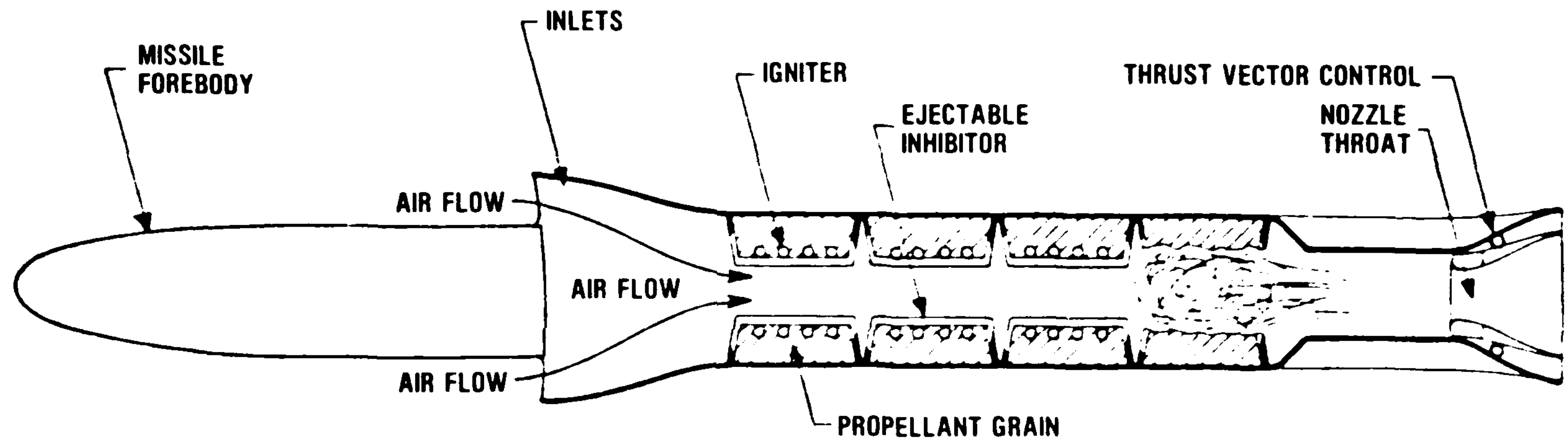

Figure 9. Schematic of Variable Mode Solid Fuel Ramjet.

USAF, has demonstrated its feasibility through full scale 12 diameter direct connect testing.

The advantages of the variable mode concept can be readily seen by comparing its flight envelope to that of a solid rocket and an airbreathing ducted rocket system, as shown in Figure 10. The air-breathing ducted rocket is limited on its inner boundary by its low thrust margin and inlet stability requirements. The solid rocket on the other hand, performs very well on the inner boundary due to its high thrust margin, but is severely limited in the outer boundary due to its short burn time. The results show that the VMSFRJ has the capabilities of the solid rocket at the inner boundary and is very nearly equal the Hydrocarbon Ducted Rocket at the outer boundary. The VMSFRJ clearly has more flexibility than either by outmaneuvering the Hydrocarbon Ducted Rocket for close-in threats at the inner boundary.

MANEUVERABILITY

The ability of the missile to kill the desired target is a function of both the target acquisition and guidance, and the missile terminal maneuver capabilities. The degree of error produced by the initial launch guidance control and the terminal seeker acquisition range will determine the number of "g" required by the missile in its terminal maneuver to the target. As shown in Figure 11, if terminal acquistion capabilities are less than 5 nautical miles very large terminal "g" maneuver levels could be required. The capability of the missile to maneuver within the lethality range of the warhead determines the kill probability of the intercept. Now, since the missile maneuvers are normally performed by aerodynamic control surfaces, the maneuver capabilities become limited at high altitudes due to the de-

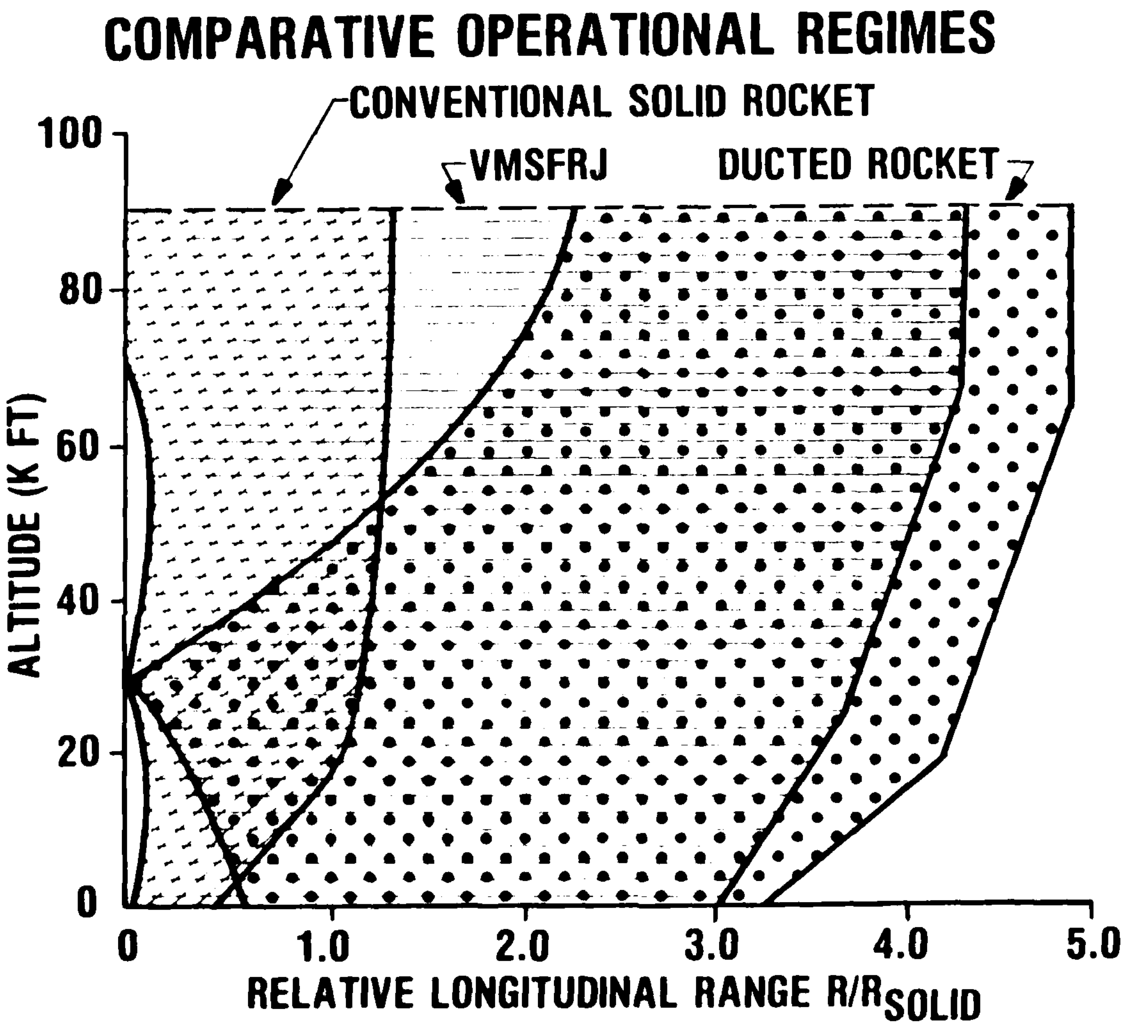

Figure 10. Comparative Operational Regimes.

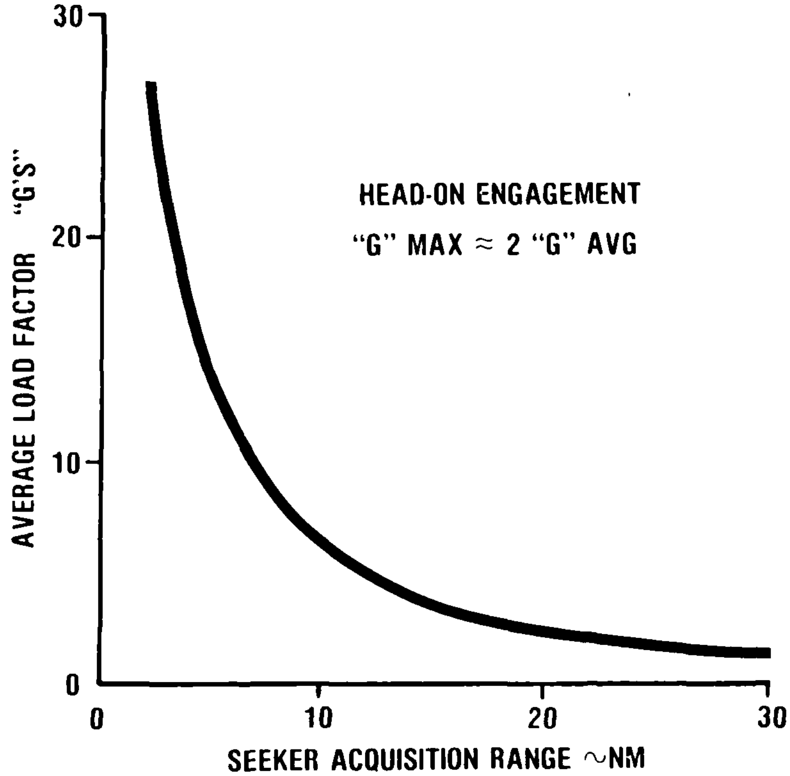

Figure 11. Missile Maneuver Requirements.

crease in dynamic pressure forces available. The use of thrust vectoring to augment the terminal maneuvers at high altitude is also limited since normally the solid rockets have burned out prior to target acquisition, and the ramjet thrust level is very low due to reduced air density. For a typical ramjet system, the resultant kill probability (Pk) as a function of altitude is shown in Figure 12. Above 50,000 ft. the kill probability falls off very rapidly due to the reduced maneuver capability. The missile maneuverability at altitude is dependent upon the missile maneuver time constants which determines the rate of charge of pitch angle and the acceleration along the desired flight path. Thus to enhance the high altitude kill probability, the missile maneuvering time constants must be reduced. Two methods are available for reducing the time constant, 1) increasing the missile pitch rate through aerodynamic lift augmentation or thrust vectoring, and 2) increasing the missile thrust level to increase the acceleration along the desired flight path. Thrust vectoring, as mentioned previously, will only be effective if the level of thrust can be substantially increased during the terminal maneuver, so increasing thrust will be beneficial for both the first and second methods of reducing the maneuver time constant.

The variable mode solid fuel ramjet concept (VMSFRJ), discussed under versatility, offers a unique method of enhancing thrust during terminal maneuvers through its energy management capabilities. With the variable mode concept, when the system is in the sustainer mode, the inlets could be shut down and the system returned to the booster mode when the terminal maneuver is enacted. This would then supply the desired increase in thrust for reducing the time constant. To achieve the maximum thrust level, the ramjet nozzle would be closed down to the smaller booster throat area. The resultant effect on thrust is shown in Figure 13 for a ramjet cruising at 80K ft. at Mach 4.0. As can be seen, over a 10 to 1 increase in thrust is available which will allow approximately a 10 "g" maneuvering increase.

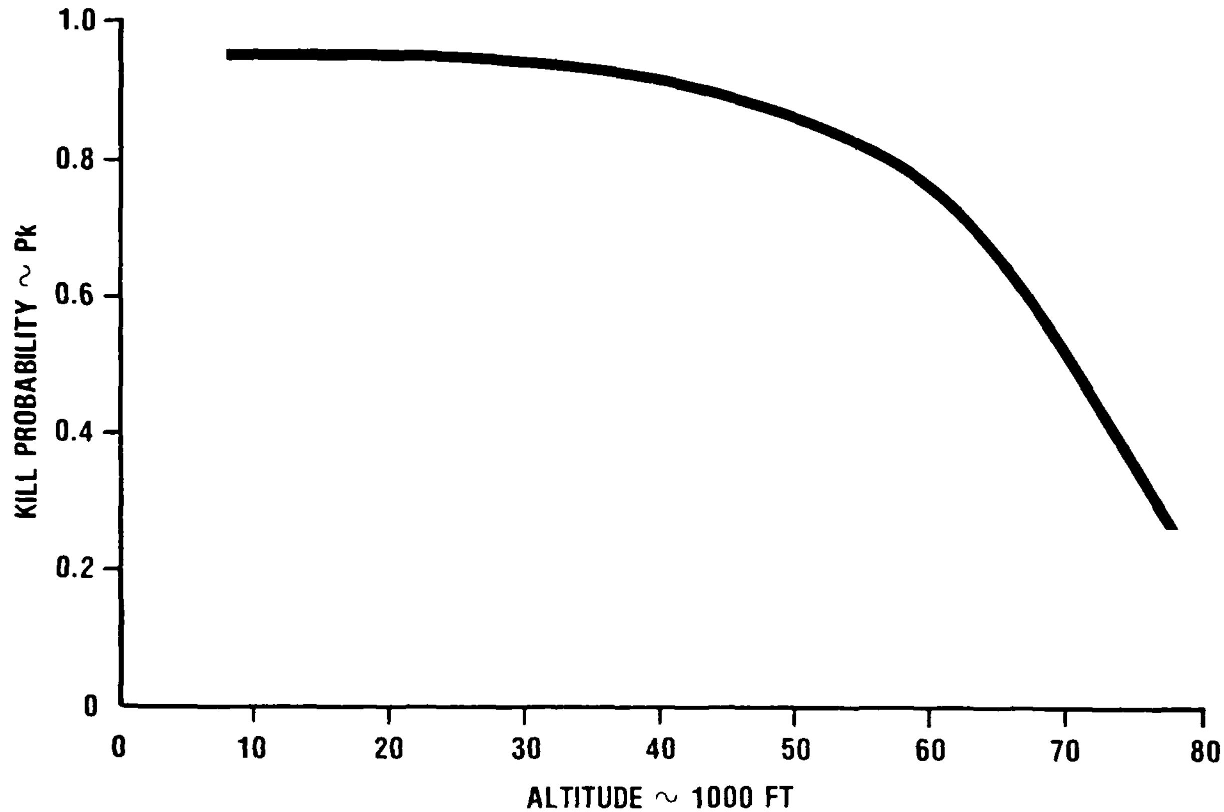

Figure 12. Effect of Altitude on Kill Probability for Typical Ramjet.

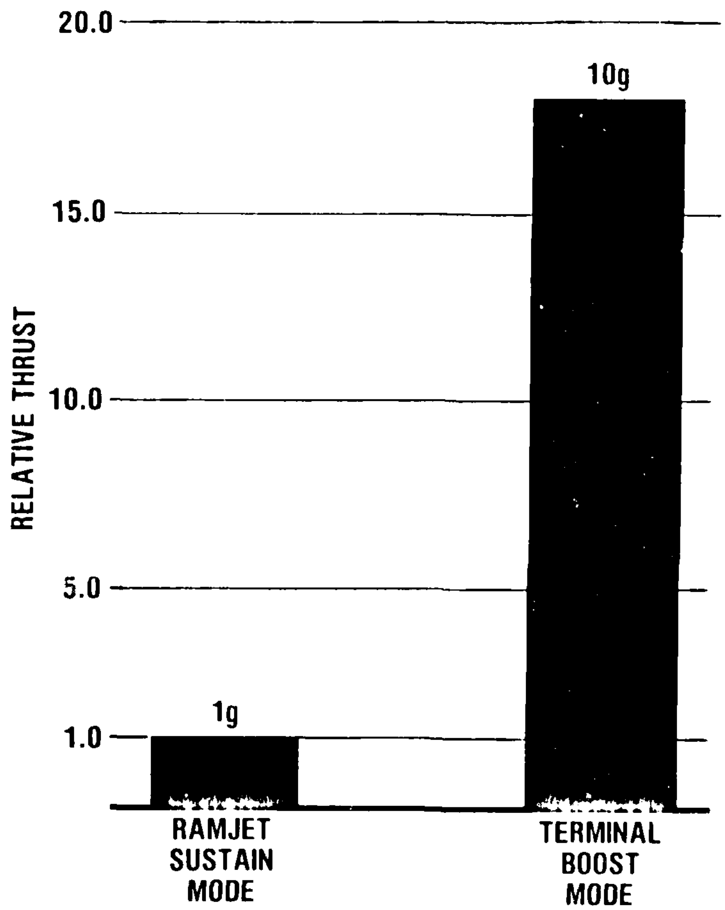

Figure 13. Effect of Terminal Boost on Thrust Level for Variable Mode Solid Fuel Ramjet.

CONCLUSIONS

The importance of propulsion technology in improving the missile systems effectiveness has been demonstrated in terms of increasing survivability and kill probability. Specific areas where the propulsion system has shown to have significant influence in the missile performance capabilities are standoff range, missile velocity, missile size, target versatility and maneuver capabilities. Within these catagories it has been shown that the use of air augmentation during the sustain phase at flight will greatly increase the missile capabilities.

The advanced solid fuel ramjet concept, with its minimum oxidizer and self-throttling capability, shows the maximum gains of the systems considered. The air augmented ducted rocket, while showing less performance advantage than the solid fuel ramjet, offers potential near term solutions to the increased standoff range and intercept velocities needed against future threats.

Evaluation of the use of advanced fuels in the propulsion systems has shown the advantages of fuels with high volumetric heating values such as boron. Integrations of boron fuel in the advanced airbreathing propulsion cycles produced significant mission advantages such as increased range, higher intercept velocities, reduced vehicle sizes, and time to target.